ELECTROSTATIC ACCELERATION OF MICROPROJECTILES TO ULTRAHYPERVELOCITIES

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ABSTRACT

A broad survey of potential techniques has led to a consistent system design for electrostatic acceleration of microprojectiles to ultrahypervelocity (> 100 km/s). The microprojectile itself is a micron-diameter carbon fiber, a few hundred microns long, charged to levels of several coulombs/kg by application of fields at the fiber surface of 10^9 V/m. Dielectric encapsulation of electrodes in a multi-plate accelerator structure allows the use of accelerating fields in excess of 10^8 V/m, with comparable fields for focusing and guiding the projectile. A reflex transmission line arrangement has been devised that permits the longitudinal accelerating field to follow the projectile motion with minimal switch action and a non-reversing electric field vector. Neutralization of the projectile charge is accomplished by thermionically-emitted electrons without disturbing the integrity of the projectile or its motion. Results of the design study, scaling of design constraints and prospects for practical accomplishment will be discussed.

I. INTRODUCTION

Over the last several years, there has been increased attention to developing techniques for accelerating solid density matter to speeds in excess of 10 km/s. Some of this attention is associated with continued interest in evaluation of the properties and behavior of material at high energy density. Further interest in very high speed projectiles is driven by the Strategic Defense Initiative, and is related to roles that might include missile intercept and decoy discrimination in space. Since space-related interests can extend to objects with relative velocities up to 10-20 km/s, it is useful to consider projectile acceleration to much higher speeds. It has been traditional to label projectile speeds that are comparable to or greater than sound speeds in normal matter (few km/s) as "hypervelocity", so speeds well beyond this range can be called "ultrahypervelocity".

For ultrahypervelocities, working fluids such as normal propellant gases or explosives have inadequate sound speeds to communicate energy efficiently to the projectile from a fixed source (at the muzzle). The real (or effective) exhaust velocity, u_e, for rocket-like techniques would also tend to be limited by thermal properties to values well below the desired projectile exit speed, u, and efficiencies of such techniques, therefore, would also be poor ($< (u/u_e)^2 \exp -u/u_e$). The ultimate communication speed (i.e., light), however, is much greater than the desired ultrahypervelocity, so electromagnetic energy transfer should be quite appropriate. High effective pressures can certainly be developed, limited only by mechanical strength, and reasonable utilization of stored energy can be anticipated. The principal difficulty is the excessive accelerator length required to launch interesting total masses with practical systems.

It is useful to review briefly some basic arithmetic for acceleration in gun systems. As an idealization, suppose a uniform and constant pressure, p, drives a projectile of mass, m, and cross section, A. Neglecting other forces, the exit speed, u, of the projectile is given by the work performed over the barrel length, L:

$$\frac{1}{2}mu^2 = pAL,$$

so

$$u = \left(\frac{2pAL}{m}\right)^{1/2} \quad .$$

The mass of the projectile may be written in terms of an average density ρ in order to define an effective (mass) length δ for the projectile:

$$m = \rho A \delta \quad .$$

The pressure driving the projectile is ultimately limited by mechanical strength of the projectile and/or barrel to a value that is proportional to the allowable material stress, S, i.e., p = KS.

The projectile speed may therefore be written as the product of a characteristic speed $u_c = (2KS/\rho)^{1/2}$, which is a property of materials (and concept details through K), and the number of projectile lengths of acceleration:

$$u = u_c \left(\frac{L}{\delta}\right)^{1/2} \quad .$$

For example, if high strength aluminum is used ($S \approx 5 \times 10^8$ pa, $\rho = 2.7 \times 10^3$ kg/m^3), then with K = 1, u_c = 608 m/s. To achieve an exit speed of $u \cong 100$ km/s would therefore require $L/\delta \geq 27{,}000$. A projectile length of common dimensions ($\delta \approx 1$ cm) thus implies a rather impractical acceleration length (L > 270 m).

The simple solution is to use a plurality of smaller projectiles. If, for our previous example, an accelerator length limit of L = 20 m is assumed, then $\delta \leq 0.75$ mm. For magnetically-propelled projectiles (of normal electrical conductivity and uniform current density), it is well-known [1] that the speed achieved before boiling divided by the conductor thickness (u/δ) is limited by thermal properties of the conductor. For aluminum, $(u/\delta) < 13.7 \times 10^6$ s^{-1}. Thus, submillimeter projectiles, under such conditions, would not be able to attain ultrahypervelocities before losing their solid integrity, while projectiles satisfying both mechanical and thermal limitations would require accelerator lengths L > 200 m. Since the magnetic field associated with the driving pressure assumed in the example is about 35 T, the accelerator structure and energy would be quite substantial. Use of superconducting or ferromagnetic materials for the projectile, in order to avoid the thermal limitation on magnetic propulsion, awaits the development of bulk materials that could operate with such high magnetic fields (or acceptance of much longer accelerators).

An additional limitation for electromagnetic accelerators that require electrical contact between barrel and projectile is heating due to friction. (Even at speeds of only 10 km/s, the kinetic energy of a carbon atom in a Lexan projectile relative to the barrel is over six electron volts; aluminum at 100 km/s has over a kilovolt per atom.) Small projectiles at ultrahypervelocity obviously cannot be allowed to touch anything before reaching their goal.

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Within the requirement to attain ultrahypervelocity solid projectiles, the only remaining approach that may be adequate is electrostatic acceleration. The present paper reviews the elements of this approach, and summarizes progress to date.

II. BASIC FORMULATION FOR ELECTROSTATIC ACCELERATION

To achieve a desired exit speed, the necessary operating conditions are obtained simply from energy delivered to a projectile with charge, q, by the accelerating field, E:

$$\frac{1}{2}mu^2 = qEL \; ,$$

so

$$u = \left(2\frac{q}{m}EL\right)^{1/2}$$

The three factors of interest clearly are the charge-to-mass ratio $\alpha = q/m$, the maximum value of the accelerating field, E, and the extent to which this field can continuously act on the projectile within the length, L. For example, to attain a speed of 100 km/s, with a maximum field of 10^8 V/m applied continuously over a length L = 20 m, would require $\alpha = 2.5$ C/kg. The effective voltage difference, V = EL experienced by the projectile is 2 GV.

The basic elements of concern in achieving electrostatic acceleration of microprojectiles to ultrahypervelocity are techniques for: 1) obtaining adequate (and consistent) values of α; 2) exerting maximum levels of electric field, (comparable to the bulk dielectric strength of materials); and 3) maintaining such field levels at the location of the accelerating projectile, without demanding component voltages and field variations that would preclude practical operation. The critical engineering task areas are, thus, charged-projectile source development, electrical insulation, and circuit design for applying a high electric field locally to an accelerating projectile.

III. CHARGED MICROPROJECTILE SOURCE

There are a number of ways to obtain a net charge on an object, including direct contact with an electrode, photon or field-induced emission and charged-particle injection. For electrically conducting bodies (field relaxation time << times of interest), the charge-to-mass ratio is simply related to the electric field at the surface E_s:

$$q = \varepsilon_o E_s A_s$$

$$m = \rho v_s$$

so:

$$\alpha = \frac{g\varepsilon_o E_s}{\rho a}$$

where the surface area A_s is related to the volume v_s and the radius of the object, a, by a geometric factor $g = A_s a/v_s$; for uniform surface charge density, g = 3 (spheres) and g = 2 (infinite cylinders), where a is the spherical or cylindrical radius, respectively. To achieve a charge-to-mass ratio of $\alpha = 2.5$ with a micron-radius cylinder of carbon fiber ($\rho = 1.8\text{x}10^3$ kg/m) would require a surface electric field, $E_s = 2.5\text{x}10^8$ V/m.

The ability to operate with a high electric field on the surface of a conductor is limited by several distinct constraints. First of all, the geometry of the microprojectile and surrounding electrodes must be tailored to allow high values of E_s at practical operating voltages. In experiments at RDA [2], surface fields in excess of 10^9 V/m have been applied to carbon fibers ($a = 3.5\text{x}10^{-6}$ m) to achieve values of $\alpha = 4.5$ C/kg with system voltages of less than 40 kV. A simple coaxial electrode geometry is used in these tests,with the carbon fiber acting as the inner (and positive) electrode, so

$$E_s = \frac{V}{a\,\ln(r_2/a)}$$

where r_2 is the radius of the outer electrode and V is the applied voltage difference.

Charged-particle emission is a second constraint on achieving high values of surface field. For $E_s > 10^8$ V/m, negatively-charged objects should be able to emit electrons quite easily. Positive charging, however, can continue up to fields in excess of a few $\text{x}10^9$ V/m. High values of α are thus more readily attained with positively charged microprojectiles. It should be recognized that the actual surface may differ considerably from the ideal case for uniform charging. Asperities at the end of cylindrical microprojectiles can experience sufficiently enhanced fields to emit ions; indeed, some ion sources are based on small-scale local enhancements of surface electric fields.

Closely related to the problem of ion emission in the slightly more macroscopic disruption of the projectile when the local electric force exceeds the available mechanical strength. For liquid droplets, this mechanical strength is due to surface tension, and the limiting value of α is given by a simple formula (Rayleigh criterion) $\alpha \le 6(\varepsilon_o\gamma)^{1/2}/\rho a^{3/2}$, for spheres with surface tension γ. The analogous relationship for (cylindrical) solids may be written as $\alpha \le (2\varepsilon_o Y)^{1/2}/\rho a$, where Y is the yield strength of the projectile material. Positively-charged projectiles can be neutralized at the exit of the accelerator simply by providing a cloud of low energy electrons (e.g., by thermionic emission). Such neutralization will heat the projectile, but not sufficiently to cause melting (since mechanical strength has already provided a lower energy density limit on the allowable value of α).

The highest values for α have been obtained with liquid droplets ($\alpha > 10{,}000$ C/kg) emitted from fine needles at high voltage. Unfortunately, the processes that provide sufficient surface electric field to create and charge droplets to such high values operate on submicron distance scales and are not amenable to control. Typically, a broad spectrum of α-values is obtained (10^3 - 10^4) with a significant angular spread to the initial droplet trajectories. In order to control the charge-to-mass ratio and eliminate undesirable perpendicular momentum due to the charging event, we have chosen to define the microprojectile size (and mass) by employing segments of carbon fiber held in a field-concentrating geometry to which a high voltage pulse is then applied. Various geometries are possible, and we have successfully used a simple hollow needle tip from which the fiber protrudes initially and is subsequently extracted by electrostatic forces during the charging process [2]. Charged microprojectiles of 7 micron diam carbon fiber, and lengths up to 5 mm, have been obtained with $\alpha > 1$ C/kg.

While this technique is adequate for laboratory study of microprojectile acceleration in strong electric fields, eventually methods will be required that allow repetitive launch of a multiplicity of fiber segments. Processes that involve statistically large numbers of particles (e.g., droplet sprays or powders) provide too broad a spectrum of particle charges and speeds to control closely the dynamics and α-value of the projectiles. It is necessary to develop microstructures that are closely controlled. One approach we have explored conceptually is the use of optical microchannel plate technology to create a plurality of properly spaced outer conductor "silos" that would each act on individual fibers serving as center conductors. The primary attraction of such an approach is that the distance between fiber launch sites can be much closer than a few fiber lengths without shielding the potential distribution needed for high surface fields along the fiber. To achieve microstructure operation at high electric field levels requires considerable attention to insulation techniques.

IV. ELECTRICAL INSULATION FOR HIGH FIELDS

There are undoubtedly a large number of particular reasons that explain the difficulty of utilizing the bulk dielectric strength of an insulator as the accelerating potential gradient in practical systems. A principal cause of problems is the so-called vacuum-metal-insulator triple point, especially at negative potentials. Basically, the free-surface of the metal electrode is capable of emitting electrons into the vacuum that then obtain sufficient energy to liberate charged-particles by impact on the neighboring insulator surface. The additional charged-particles can also gain sufficient energy from the field to create further ionization along the insulator surface, leading quickly to an electrical discharge. It is now standard practice to diminish the probability of such a discharge process by arranging electrode and insulator geometries so that the triple-point occurs only in regions of low field (at least along the insulator). For systems, such as the present microprojectile accelerator, that do not require direct electrical contact, it is not necessary to have a triple-point at all.

By completely encapsulating electrodes in a high dielectric strength material, it is possible to prevent the acceleration of emitted electrons to high energy and the conditions for insulator flashover. For systems involving charged-particle beams and/or long-term, repetitive operation (e.g., high voltage AC power lines), it might be expected that charging of the dielectric coating and partial discharges within the coating material would eventually degrade the protection offered by encapsulating the accelerator electrodes. Successful tests [3] at rates of 200-400 Hz (in sixty pulse bursts) at 4×10^7 V/m indicate that adequate performance may be possible for microprojectile acceleration. In related studies [3], elimination of the vacuum-metal-insulator triple point has been shown to increase the allowable electric field strength between accelerator electrodes, with the demonstrated performance increase limited only by the capabilities of the experimental apparatus (and in some cases, by the mechanical integrity of the insulator). While an extended data base for very high field operation must still be generated, the preliminary results suggest that the basic encapsulation concept will remain sound.

V. ACCELERATION OF MICROPROJECTILES AT HIGH FIELDS

The ability to generate accelerating fields in excess of 10^8 V/m using components at hundred kilovolt levels depends first of all on relatively small inter-electrode gaps (e.g., $\Delta Z = 1$ mm). Furthermore, the application of voltage to the electrodes in the vicinity of the microprojectile must be sequenced in a manner that enhances the stability of the projectile motion. For example, aperture focusing can be used to establish a higher electric field in the direction of projectile motion. More generally, a succession of electrodes near the projectile could be subjected to a voltage distribution that locally creates a positive field gradient along the field direction. (For sub-millimeter projectile lengths, the total voltage difference associated with the distribution could remain about a hundred kilovolts, while maintaining the desired high electric field, but the electrode thickness, separation, edge radii and encapsulation thickness would all be submillimeter.)

It is necessary for this voltage distribution to follow the projectile acceleration along the length of the accelerator. Three electrical engineering challenges exist here: 1) creation of an accelerating distribution through a sequence of uniformly spaced electrodes; 2) moving this distribution over a range of speeds that are much less than the speed of light; and 3) performing (1) and (2) with a minimal number of components (e.g., switches) in a manner that is both efficient and avoids significant reversal of the electric field vector in the dielectric. The first challenge includes the condition on uniform spacing in order to obtain the highest average field gradient along the total accelerator with modest component voltages. The second challenge introduces the need for lumped components, acting, however, in a quasi-continuous fashion. The last challenge combines an overall desire for system simplicity (in the face of twenty meters worth of submillimeter electrode structure) with a concern that significant and repetitive reversal of electric field applied to insulation is deleterious to long term electrical strength.

In addition to these challenges, it is useful to note a few numerical aspects of the microprojectile accelerator system. For example, an exit speed of 10^5 m/s achieved by constant acceleration over a distance of 20 m implies a flight time for a single projectile through the accelerator of 400 μs. At uniform field gradient, equal energies are given to the projectile in equal lengths of the accelerator. The projectile thus achieves about seventy percent of its final speed half way along the accelerator, after about 300 μs. In the last stages of acceleration, the characteristic pulse time of the voltage gradient (distributed over distances of about 1 mm) will be about 10 ns, while at the initial stage of acceleration, this time may be measured in microseconds. There is thus a considerable range of circuit values needed within the single compact accelerator system.

There are (at least) two distinct ways to provide a voltage gradient that will follow the projectile along the accelerator: 1) active switching to each electrode by an array of controlling electronics; and 2) matching the motion of the projectile by proper *a priori* connections to a distributed transmission line along which a voltage pulse is propagating. The former technique may be adequate for operation with a limited number of projectiles (e.g., in high energy density impact studies). The latter approach could be used for situations in which the total energy in a microprojectile burst would demand transient currents beyond the capability of a large-scale array of controlling electronics. For example, a carbon fiber projectile 2 microns in diam and 500 microns long has a mass of $9\pi \times 10^{-13}$ kg, and, with $\alpha = 2.5$ C/kg, a charge of 7.07 pC. The accelerator electrodes would have minimum areas scaled by the projectile length. If the minimum effective diameter is 2 mm, then, with an interelectrode spacing of 1 mm and a dielectric constant of three, the minimum capacitance of an electrode pair is less than 10^{-1} pf. Circuits for a small-scale (low projectile number) accelerator would probably be designed to avoid problems with stray capacitances (of a few pf), so minimum capacity values of > 10 pf would be required. At $V = 10^5$ v, the total charge to be manipulated is then $> 10^{-6}$ C (which is much greater than a single projectile charge). For the initial stages of the accelerator, the associated transient currents are less than 10^{-1} A, while the final stage currents may exceed 10 A. Such values could be consistent with active electronic control.

If large total amounts of projectile energy are desired, then circuit operation will become dominated by the usual pulsed power concerns of energy and current delivery. For the previous example , at u = 100 km/s, the exit kinetic energy of the projectile is 1.4×10^{-2} J. If a 100 kJ of total energy in a cloud of microprojectiles is the design goal, then the burst will contain 7.1 million microprojectiles. The total charge on the projectiles is 5×10^{-5} C, so the driving circuit capacitance values should easily exceed stray capacities. At an average power of 100 kW, the average current to the accelerator would only be a few amperes. The transient currents within the accelerator, however, would vary in value, with the highest levels occurring in the final stages. If a 400 Hz repetition rate is allowed within a one second microprojectile burst, then the microprojectile charge in the final stages would be 1.25×10^{-7} C, so minimum currents to the electrodes should be 0.1 - 1.0 kA.

Keeping in mind the rather large number of stages for a full accelerator length of 20 meters (N > 20,000), replication of components for operation with high transient currents suggests that at least part of the accelerator driving circuit should be based on a passive arrangement with reduced switching needs. An arrangement under development at RDA is called a Reflex Transmission Line. Basically, a slow current source, such as a large capacitor (or LCL inductive transfer system), is used to energize an inductive store in the form of a transmission line shorted at one end. Delivery of current to the line occurs on a timescale that is long compared to the line transit time. At peak magnetic energy, the current in the line is interrupted at the open end of the line, resulting in a high voltage that propagates down the line. (The circuit interruption occurs effectively with a capacitive shunt and the circuit energy already stored downstream, so the opening switch does not require significant energy dissipation). The voltage gradient for the accelerator electrodes is obtained by sampling the line voltage at appropriate positions. After the high voltage pulse reaches the shorted end of the line, the V = 0 condition propagates up the line (converting electrostatic energy back into magnetic energy), with the electric field vector, however, remaining in the same direction in the accelerator. At the upstream end of the line, the transmission line, now serving again as an inductive store, can be connected to the original capacitor (or LCL) to preserve the circuit energy for a subsequent pulse. With an LC-ladder network of lumped elements for the transmission line, the rather long transit time required to match the relatively slow microprojectile velocity (vs light) can be obtained in reasonable dimensions. From circuit analyses, it appears that about three to five LC-sections are needed to "capture" the complete voltage gradient. Additional studies will be evaluating the best match of line segments to the various portions of the accelerator (i.e., slow to fast).

VI. CONCLUDING REMARKS

The problem of achieving ultrahypervelocity (> 100 km/s) solid projectiles is indeed a challenging one. Its solution requires extending pulsed power techniques to the extremes of electromechanical strength, while preserving some basis for implementation of these extreme values in a practical system. Calculations and present experimental results indicate that it is possible to utilize electrostatic techniques to generate sufficiently charged microprojectiles and to accelerate these projectiles stably through a succession of electrode stages. The application of these techniques, however, to studies of ultrahypervelocity impact of relative large masses (> nanogram) and strategic defense in space will require further effort to demonstrate higher projectile speeds (i.e., many more electrode stages), improved source handling, and optimized pulsed power systems.

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